

Correlation between clinical performance and degree of conversion of resin cements: a literature review

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ABSTRACT

Resin-based cements have been frequently employed in clinical practice to lute indirect restorations. However, there are numerous factors that may compromise the clinical performance of those cements. The aim of this literature review is to present and discuss some of the clinical factors that may affect the performance of current resin-based luting systems. Resin cements may have three different curing mechanisms: chemical curing, photo curing or a combination of both. Chemically cured systems are recommended to be used under opaque or thick restorations, due to the reduced access of the light. Photo-cured cements are mainly indicated for translucent veneers, due to the possibility of light transmission through the restoration. Dual-cured are more versatile systems and, theoretically, can be used in either situation, since the presence of both curing mechanisms might guarantee a high degree of conversion (DC) under every condition. However, it has been demonstrated that clinical procedures and characteristics of the materials may have many different implications in the DC of currently available resin cements, affecting their mechanical properties, bond strength to the substrate and the esthetic results of the restoration. Factors such as curing mechanism, choice of adhesive system, indirect restorative material and light-curing device may affect the degree of conversion of the cement and, therefore, have an effect on the clinical performance of resin-based cements. Specific measures are to be taken to ensure a higher DC of the luting system to be used.

Keywords: Dental prosthesis retention. Dental materials. Luting agents. Biocompatible materials.

INTRODUCTION

Resin cements are composite resins developed to deliver mechanical properties and handling characteristics that are important for luting indirect restorations. These cements contain different monomers, which are linked together during the polymerization reaction. Due to their application under an indirect restoration, in most cases the physical activation (photo activation) has very limited effect¹⁴. Therefore, there is a need for chemical activators. Activation of the polymerization means to induce the photo initiator (e.g., camphorquinone) or to break the molecule of the chemical initiator

(benzoyl peroxide) so as to form free radicals that will initiate the polymerization. Free radicals link to monomers by breaking carbon-carbon double bonds. The continuous addition of monomers to a growing chain results in a polymeric chain. In general, the maximum degree of conversion (DC) – the percentage of aliphatic C=C (double) bonds converted into C-C (single) bonds to form the polymeric network – reached by resin cements is around 60%,⁴³ due to the increase of cement viscosity during the polymerization reaction, hindering the mobility of the reactive species⁴⁹. The reaction slows down progressively up to a moment when new bonds cannot be made⁷¹.

Resin cements have been frequently employed for bonding indirect restorations to the teeth due to their mechanical behavior³⁴ – superior to conventional cements (resin-free) –, possibility of adhesion to the restorative material⁵⁰ and to the tooth structure with⁷ or without an adhesive system⁶⁰, and superior optical properties³⁶ when compared with conventional cements. However, limitations associated with the incomplete polymerization (low DC) of the cement may result in higher sorption and solubility values⁶⁷, causing faster degradation of the cement finish line by the acids present in the oral biofilm⁶⁷. Degradation of resin-based cements reduces the bond strength between them and the substrate³⁹ and causes dissolution of the finish line at the restoration margin, which may mean the clinical loss of the restoration either by debonding, fracture or secondary caries²⁰. Unreacted monomers (not bonded to the polymeric chain) may also irritate the pulp and generate a local inflammatory response¹⁸.

There are multiple factors that may interfere with the DC of resin cements and, therefore, compromise the longevity of indirect restorations. Some of them are the material composition (monomers and other components of the activation system)⁵⁶, possible inadvertent interactions between the bonding system and the cement⁶³, characteristics of the restoration to be cemented (optical properties and thickness of the restoration)^{14,15} and characteristics of the photo activation step³². This article aims to perform a comprehensive review of the factors involved in the DC of the resin-based luting systems and the impact of DC on luting system properties.

CURING MECHANISM

As previously mentioned, photo-activated or light-activated resin cements are indicated for situations where the light of the curing unit may pass through the restoration, such as translucent veneers and shallow inlays⁵⁶. These cements are provided in a single paste with a photoinitiator system composed of a photosensitive component (usually camphorquinone) and a tertiary amine. The presence of light with a wavelength of 480 nm (blue region of the visible spectrum) activates camphorquinone⁶⁹, which binds to the tertiary amine and then releases two free radicals that will start the monomers conversion. Photo-cured resin cements have unlimited working time, with the polymerization starting right after the exposure of the material to light⁴.

Chemically cured (self-cured) cements are indicated under thick restorations, for luting intrarradicular posts and crowns made of materials that block the light, such as metallic copings or highly opaque ceramics^{42,68}, aiming to guarantee

maximum properties over time in areas that light energy is unable to reach⁷¹. The limitations of these systems are the reduced working time as opposed to the extended setting time⁷⁷ and the tendency to become “yellowish”, due to the higher concentration of tertiary amines (activators)²⁹. The polymerization reaction in self-cured cements requires the components of the activation system – tertiary amine and benzoyl peroxide – to get in contact by the mixing of two pastes, base and catalyst.

Dual-cure resin cements were developed in an attempt to combine the benefits of both photo and chemically activated systems^{16,56,77}, obtaining optimized DC in the deepest locations under a restoration, controlled working time and short setting time. In such systems, there is a catalyst paste with a chemical initiator, usually benzoyl peroxide, and a base paste containing the photo-cured resin cement and the tertiary amine responsible for the activation of the self-cure reaction⁵⁷. When both pastes are mixed together and exposed to light, the polymerization happens by physical (photo) and chemical (redox) activation. The appropriate working time is controlled by inhibitors of the self-cure reaction or by the amount of activators of the polymerization⁵⁶. It is expected that in areas where there is not enough light, the interaction between the tertiary amine and benzoyl peroxide will be enough to ensure the cement polymerization^{4,57}. However, when not properly photo-activated, dual-cure resin cements may present reduced DC^{47,49,77}, which implicates in lower hardness⁵⁷, higher solubility⁷¹, lower flexural^{11,57} and compressive strengths, and lower bond strength to dentin in comparison to directly light-cured dual cements^{7,77}. For instance, a self-adhesive dual cement applied in self-curing mode may show DC as low as 11% after a 10-minute setting time⁷⁷. Considering the clinical application of the resin-based luting systems, which are used for the cementation of indirect restorations onto tooth structure, 10 min is an undesirably long time for a luting agent to obtain a great percentage of the optimal setting characteristics, without compromising the integrity of the margins and the cement layer under functional loading^{8,77}.

In general, light-cured and dual-cured cements activated by light through a restoration thinner than 2.0 mm^{4,36,44,75} have higher DC than self-cured cements⁷⁷. When a dual cement is self-cured (no activation by light), mechanical properties such as flexural strength, modulus and hardness are reduced by 68.9%, 59.2% and 91.1%, respectively, in comparison to original values presented by dual-cured samples³⁴. There are different factors that may affect the DC of self-cured luting systems, such as the relatively high concentration of polymerization inhibitors used to extend the material's shelf life and

to provide a clinically viable working time, ranging from 2 to 5 minutes, which adversely inhibits polymerization during the luting procedure⁶¹; the slow rate of polymerization activation and subsequent propagation of radicals in comparison to a directly light-activated material^{6,49,51,61}; and the low concentration of benzoyl peroxide incorporated into those materials^{6,49}. Furthermore, the hand-mixing of the two pastes incorporates air bubbles that further inhibit polymerization due to the presence of oxygen⁷⁹ and may act as stress concentrators that potentially result in cracking throughout the cement layer⁵⁶. Although it has been demonstrated that the high incidence of air voids reduces the stress generated by the polymerization shrinkage of the cement due to a change in ratio of bonded to unbonded surfaces⁵, the clinical benefits of the inclusion of pores have not been determined. Pores are also incorporated in dual-cured cements during mixing and they may become an esthetic concern when cementing veneers¹⁶. To minimize the undesired consequences of the hand-mixing procedure, some manufacturers provide cements in a self-mixing apparatus (Figure 1), which eliminates the manual mixing step, generates a homogeneous mix and reduces the incorporation of bubbles. However, voids have been observed after automatic mixing as well⁵⁶.

Interestingly, if light incidence on the cement layer is significantly compromised, the chemical activator of dual cements improves DC when compared to photo-activated-only systems^{1,7,15,16} but the efficacy of the self-curing mode is still controversial^{8,14,49} and varies from one material to another⁴⁴. It has been demonstrated that the absence of the self-curing component in light-activated systems negatively affects the DC of these cements when the light-curing component is not able to guarantee an acceptable degree of conversion, for example when applied underneath onlays of greater thickness¹. Considering a clinical application in which almost no light reaches the cement layer, it is desirable to use dual resin cements that present a chemical curing mechanism as efficient as photo-curing⁸. However, there is currently no resin luting system in the market capable of overcoming this limitation^{2,7,45}. In general, the chemical activation of dual cements does not seem enough to compensate for the absence of light under thick or opaque restorations, even 24 hours after the beginning of the activation^{1,15,32,61,64,65,75}. The DC of a self-adhesive dual cement may vary from 37% when light-cured for 20 seconds⁷⁷ to 58% when light-cured for 40 seconds⁴³, evidencing that there is also a direct correlation between light intensity received by a photo-activated material and its DC^{14,46,49}. Laboratorial studies bring evidence that the activation time generally recommended by the

manufacturer (Figure 1) is not sufficient to result in maximum degree of conversion^{27,77}. Therefore, when highly opaque or thicker restorations need to be employed, a prolonged light exposure time is recommended (please read "Indirect Restorative Material" below), since a gradual increase in light-curing time and, therefore, in light transmission, gradually increases the Knoop hardness of resin-based luting systems⁶⁴. Additionally, the use of a dual-cure system should always be considered to possibly increase the DC by means of a chemical activation of the monomeric system.

With regard to post-activation time, the 24-hour DC of light-cured and dual-cured cements is directly related to the DC obtained right after light exposure^{4,75}. Even though DC is maximized during the first 30 minutes after light activation^{2,79}, some cements present gradual increase in DC for up to 24 hours, mainly when used in the dual-curing mode^{4,10,28,31,64,79}. However, it has been speculated that a delay in light activation of dual-cured materials would enhance their properties⁵⁶ by allowing the self-polymerization promoters to react at some extent before being entrapped by the polymeric chains as soon as the photo-activation begins^{49,74}. Delaying the light activation for 2 min may, for instance, compensate for a lower dose of light reaching the cement layer⁴⁹, but no effect is observed on the bond strength of resin cements to the substrate²⁸. On the other hand, prolonged self-curing of the cement may also compromise the overall DC⁴⁹ and increase water sorption⁷¹ when light activation is delayed for 10 min for the same reason, indicating that an ideal balance between self-curing and photo-activation is yet to be determined.

Under ideal circumstances, light-activated resin cements show higher DC than chemically cured resin cements, irrespective of brand names^{49,57}. However, the DC of dual-cured cements is material-related, which means that it is more associated with the brand name than with the material classification *per se* and some systems are significantly more dependent on light activation than others^{1,10,11,15,16,31,51,73,79}. Just as an illustration, the DC of a given dual-cured cement (RelyX ARC, 3M Espe, St. Paul, MN, USA) may vary from 81% to 61% when cured under light as opposed to total absence of light respectively, and from 56% to 26% when another dual-cured cement (RelyX Unicem, 3M Espe, St. Paul, MN, USA) is cured under the same conditions⁴³. This difference may be explained by the difference in composition between both materials. For instance, some resin-based cements present twice as much benzoyl peroxide than others⁵¹. The lower DC may affect some critical properties of the resin-based cements⁶⁴. Dual cements cured under a dual mode (photo+chemical) present lower toxicity and solubility than dual cements

Activation mode	Adhesive strategy	Brand name& Manufacturer	Commercial presentation	Recommended curing time ^θ	Characteristics (Ref #)
DUAL-CURED	Self-adhesive	Bissem Bisco	Self-mixing applicator	20-30 s or 8 min*	DC of 41.5% ⁷⁶ Higher DC (86%) with dual-curing mode and longer measuring time interval ²
		Maxcem Elite Kerr	Self-mixing applicator	10-20 s on each surface or 4-5 min**	Low cytotoxicity ⁶⁴ DC of 26.4% ⁷⁶ Low bond strength (7.76 MPa) to Y-TZP ⁷⁹ High shrinkage strain at different temperatures ³⁹ Relatively high DC (68%) 10 min after light curing for 40 seconds ³⁰
		RelyX Unicem 3M ESPE	Capsules or self-mixing applicator	20 s on each surface or 5-6 min*	DC of 37.3% ⁷⁶ Mild cytotoxicity ⁶⁴ Good bond strength (21.1 MPa) to Y-TZP ⁷⁹ Relatively high contraction stress and microhardness after light curing for 40 seconds ³⁰
		SmartCem 2 Dentsply Caulk	Self-mixing applicator	20-40 s on each surface or 6 min*	Low shrinkage strain at different temperatures ³⁹ Low water solubility and high DC after 4-min curing delay ²⁰ High water solubility and reduced DC after 4-min curing delay ²⁰ Reasonable shrinkage strain at different temperatures ³⁹
		SpeedCem IvoclarVivadent	Self-mixing applicator	20 s on each surface or 160±40 s**	Reasonable shrinkage strain at different temperatures ³⁹
	Conventional	Clearfil Esthetic Cement Kuraray Inc.	Self-mixing applicator	20 s or 3 min*	Low bond strength (1.1 MPa) to superficial dentin ⁵¹
		Duolink Bisco	Self-mixing applicator or two syringes	40 s on each surface or 3 min 30 s**	Relatively high contraction stress and microhardness after light curing for 40 seconds ³⁰
		Multilink Automix IvoclarVivadent	Self-mixing applicator	20 s on each surface or 180±30 s**	DC of 61.4% ⁷⁶ Good bond strength (31.7 MPa) to Y-TZP ⁷⁹ Low bond strength (3.1 MPa) to superficial dentin ⁵¹
		Nexus Third Generation Kerr	Self-mixing applicator	20 s on each surface (no info available on self-curing)	Reasonable shrinkage strain at different temperatures ³⁹ Very low bond strength to dentin under self-curing mode ⁴⁴ High DC (84.8%) one week after light curing for 100 seconds ⁴⁵
		Panavia F 2.0 Kuraray Inc.	Two syringes	20 s on each surface or 3 min**	Inferior bond strength to resin composite (10.7 MPa) in different activation modes ²⁷ DC (~78%) not influenced by the curing mode – self- or dual-curing –, but influenced by measuring time ² Low bond strength (5.5 MPa) to superficial dentin ⁵¹
		RelyX ARC 3M ESPE	Self-mixing applicator	40 s at the margins or 10 min**	8.1% of secondary caries under crowns after 5 years in clinical service ⁶⁵ In combination with a modified crown design, provided the greatest fracture strength to an indirect restoration ⁶⁶ Fast curing and high DC ⁷⁸
		RelyX Ultimate 3M ESPE	Self-mixing applicator	20 s on each surface of 6 min*	Superior bond strength to resin composite (16.5 MPa) in different activation modes and testing times ²⁷ DC of 63% when light-cured under a 2 mm thick composite resin slab at room temperature ²⁹ High water sorption and solubility ⁷⁰
		Variolink II Ivoclar Vivadent	Two syringes	40 s on each surface (no info available on self-curing)	Very low bond strength to dentin under self-curing mode ⁴⁴ Relatively high DC (72%) one week after light curing for 100 seconds ⁴⁵
SELF-CURED	Conventional	C&B Cement Bisco	Self-mixing applicator or two syringes	4 ~ 7 min*	No measurable microhardness up to 10 min after mixing and low DC after 7 days ⁷⁸
		Panavia 21 Kuraray Inc. Superbond C&B Sun Medical	Two pastes Powder and liquid in different containers	~4 min 30 s* 7 min 30 s-9 min 30 s**	Low cytotoxicity ⁶⁴ 3.4% of secondary caries under crowns after 5 years in clinical service ⁶⁵ High bond strength to both superficial (15.5 MPa) and deep (12.5 MPa) dentin ⁵¹
LIGHT-CURED	Conventional	Choice 2 Bisco	One syringe	40 s over the veneer	~59% DC 7 days after light activation ⁷⁸
		RelyX Veneer 3M ESPE	One syringe	30 s on each surface	Reduced DC when 1.5 mm or thicker veneers are used ⁵¹

&Brand names mentioned were reproduced from the research papers included in this literature review. Therefore, there may be other brand names currently in the market that would represent the categories of materials described in this Table. ^θLight-curing time recommended for QTH or LED curing devices. Dual and self-curing times may either consider room temperature (~23°C) or mouth temperature (~37°C). *Time after starting the mixture. **Time after placement of prostheses

DC=degree of conversion; LED=light-emitting diodes; QTH=Quartz-tungsten-halogen

Figure 1- Summary of some resin-based luting systems currently available and their characteristics based on the papers included in this review. Composition may vary significantly among different materials

cured under the self-curing mechanism (chemical only)^{55,65}. Dual curing also leads to a rapid increase in hardness whereas chemically cured specimens are still soft 30 minutes²² or even one hour⁶⁴ after mixing. Dual-curing mode also results in improved bond strength⁴⁴ and mechanical properties such as flexural strength, modulus and hardness, in comparison to light curing or chemical curing only^{34,64}.

Adhesive and self-adhesive resin cements have functional monomers such as 10-methacryloyloxydecyl dihydrogen phosphate (10-MDP), 4-methacryloxyethyl trimellitate anhydride (4-META) and phosphoric esters. These resin cements generally have a dual-cure mechanism. Self-adhesive cements have acidic functionalities in order to demineralize tooth structure²³, and an acid-base reaction between the acid groups of the monomers and the glass filler of the core material or the mineralized tooth surface starts immediately after the mixing of the components and application of the cement on the tooth surface³¹. However, those acidic monomers have been shown to negatively affect the cement degree of conversion, since they interfere with the amine initiator⁷⁷. This interference compromises both the self-cure and the dual-cure modes⁷⁶. The very low polymerization shrinkage strain of some self-adhesive cements may also be an evidence of reduced DC⁴⁰. Indeed, there is a significant variation between the DC of different materials^{31,40} and increasing the light-exposure from 20 s to 40 s does not improve DC values after 6 hours³¹ as much as a temperature increase of the cement improves⁴⁰. However, when the absence (self-cure) and the presence (dual-cure) of photo-activation are compared, the presence of light may result in a 10-fold increase in the material degree of conversion⁴⁰. Although another initiator system based on sodium aryl sulfate or aryl-borate salts has been proposed⁷⁰ to compensate for the interaction between acidic monomers and the amine initiator in self-adhesive systems, no evidence has been found of any significant improvement in the DC for sodium persulfate-containing materials^{8,77}.

Another way to improve the polymerization kinetics of resin-based luting systems is to increase the temperature of the material^{30,51}. High viscosity cements have significantly lower degree of conversion than low viscosity cements²⁴, probably due to the reduced mobility of the monomers in viscous materials. Increased temperature prior to and during polymerization leads to higher DC, due to increased free radical and monomer mobility^{1,21} and collision frequency of the unreacted active groups resulting from the decrease in the viscosity of the material^{21,30}. However, pre-heating (50°C) dual-cured resin cements with a higher concentration of the chemical activator (benzoyl peroxide) may

result in significant decrease in working time, thus compromising the clinical application of the material^{30,51}, and still may not compensate for the absence of light³⁰. The clinical applicability of the pre-heating technique is questionable, since the tooth structure could not be possibly heated up to 50°C, which would immediately result in the cement temperature decrease. Therefore, any evaluation on this topic should limit the pre-heating temperature to 37°C⁵¹.

BONDING AND CEMENTATION

The bonding between resin cement and the tooth structure (or the core build-up material) is generally made possible by the use of a self-adhesive resin cement or by the application of a bonding agent/system. The bonding agent/system may either be self-etch or total-etch (etch-and-rinse)¹³. However, there are restrictions for the application of some simplified adhesive systems, more precisely two-step total-etch (primer and adhesive in one bottle) and "all-in-one" self-etch systems and resin cements with some chemical activation, either self-cured or dual-cured³⁷. It has been shown that the lower the pH of the bonding agent employed, the lower the bond strength between self-cured cement and dentin⁶³. The use of a simplified adhesive bonded to a self-cured cement results in 10-50% of the bond strength presented when the same adhesive is bonded to a light-cured cement⁶³.

The reason for those diminished bond strength values is that when simplified-step adhesives are used together with chemical-cured cements, there is an interaction between the residual acidic monomers from the adhesive inhibition layer and the binary peroxide-amine catalytic components that are commonly employed in chemically cured resin composites⁶³. Therefore, the tertiary amine of the resin cement is neutralized and does not react with the initiator, resulting in low bond strength at the adhesive-cement interface¹⁹. Besides that, the adhesive layer of simplified systems (all-in-one) is highly permeable to dentinal fluids due to incomplete polymerization^{12,13}, and these are then kept at the interface between the adhesive and the cement, compromising the bonding between those two substrates^{19,72}, which is demonstrated by exclusively adhesive failure modes⁶³. To maximize the performance of the resin cements, self-cured or dual-cure cements are to be employed only in association either with three-step total etch systems or with self-etching primer systems containing a separate bonding agent. For all of the other adhesive systems, the resin cement employed should be exclusively photo-activated.

INDIRECT RESTORATIVE MATERIAL

When photo-activation of a resin cement is performed, part of the visible light that reaches the crown is transmitted through the restoration, part is absorbed and part of it is reflected on the surface⁵⁷. Consequently, the light intensity that effectively reaches the cement varies according to the optical characteristics of the restorative material^{15,62}, such as opacity^{14,44} and shade^{8,53}, and the final thickness of the restoration^{15,25,48}. The higher the thickness and the lower the value (darkness) of the restoration, the lower the light intensity reaching the cement layer, which may compromise the DC of a given cement^{15,47,57,79}.

There are many restorative systems nowadays that may be used for the manufacturing of all-ceramic crowns (Figure 2). Each one of these ceramic systems has a microstructure that directly interferes with the amount of light that may be transmitted through the restoration^{14,78}. Considering restorations with similar shade and thickness, ceramics with a higher number of light scattering centers (interface between different microstructural phases) are more opaque and prone to block visible light^{14,33,57,58}, compromising the intensity of the physical polymerization of the resin cement⁵⁷. Pores, frequently found in feldspathic porcelains and glass-infiltrated composites due to the processing method of these materials, act as light scattering centers as well. Light scattering occurs at interfaces of different phases with dissimilar refraction indexes. A free of pores porcelain would be a material with no light scattering interface and would thus show transmittance, resulting in high DC for dual cements even under a 3 mm-thick layer¹⁵. A multi-phase material would scatter the light because the incident light beam will change direction from one phase to another and the result will be a weaker incident light. A multi-phase structure within a material also results in light scattering and low transmittance¹⁴. Thereafter, glass-infiltrated alumina-zirconia (In-Ceram Zirconia System, Vita Zahnfabrik, Bad Säckingen, Baden-Württemberg, Germany) is the most opaque alternative among current clinical options, due to the presence of four distinct phases with different refraction indexes (alumina, Ceria-stabilized zirconia, lanthanum glass and pores), with a final maximum transmittance of only 6% in 0.5 mm-thick copings, and when the thickness of the same material increases to 1.5 mm the transmittance becomes as low as 1% of the initial light intensity. Glass-infiltrated spinel ceramic (In-Ceram Spinell, Vita Zahnfabrik, Bad Säckingen, Baden-Württemberg, Germany) presents significantly higher transmittance because it has only two phases (glass and spinel), with similar refraction indexes.

When comparing the translucency of lithium-disilicate glass-ceramic and leucite-reinforced glass ceramic, Illie, et al.³⁶ (2008) observed that the first is more opaque than the latter (Figure 2). Lithium-disilicate glass ceramic contains a main crystalline phase of "elongated crystals building a scaffold of many small interlocking needle-like crystals randomly oriented"³⁶, with a second crystalline phase consisting of lithium orthophosphate³⁵. On the other hand, leucite-reinforced glass-ceramic is a less dense material, characterized by the single crystal formation of leucite crystals^{35,36}, indicating that lithium-disilicate ceramics scatter more light than leucite ceramics. Light delivered to the cement layer through lithium-disilicate ceramic (shade medium opacity 1) is reduced to 45% under 1 mm ceramic slabs, 16% under 2 mm slabs and approximately 8% under 3 mm slabs⁸⁰. Leucite-reinforced glass ceramic slabs reduce the light transmittance to 80%, 64% and 43% under 0.7, 1.4 and 2.0 mm thick samples, respectively⁴⁷.

As previously mentioned, the relationship between restoration thickness and transmittance is highly dependent on the opacity of the material^{14,51,54,80}. However, the impact of the amount of light reaching the cement layer on its DC is controversial. Dual-cure resin cements activated by light under a 1.5 mm lithium-disilicate glass ceramic (Shade A2 low translucency) surface presented a DC similar to that of cements cured under direct light exposure⁵¹, whilst samples cured through 1.4 mm-thick leucite-reinforced glass-ceramic slabs may⁵⁴ or may not⁴⁸ show significantly lower hardness values than groups activated with direct light exposure, depending on the luting system employed. In another study, samples light-cured under 1 or 2 mm thick lithium-disilicate slabs only showed decreased hardness when light exposure time was 20 s or less, indicating that longer exposure times may compensate for light attenuation of the indirect restorative material⁸⁰. A randomized clinical split-mouth study evaluating the longevity of glass-infiltrated alumina crowns cemented with three different cements (two resin-based and one glass-ionomer) evidenced acceptable survival rates for all groups, with dual-cured cements showing higher survival rate than glass-ionomer cement, indicating that the opacity of the crown did not affect the performance of the cement/restoration⁶⁶. It is important to remember that the final absolute transmittance values of a restoration would be even more compromised considering the thickness and the optical characteristics of the porcelain veneer layer¹⁴. The DC of a dual-cured cement activated under glass-infiltrated alumina (1.2 mm thickness) with porcelain veneer layer (0.8 mm thickness) is significantly reduced when compared to feldspathic porcelain samples (2 mm thick) and to the control

Material	Brand name& Manufacturer	Sample characteristics	Photo-curing conditions	Findings (Ref #)
Lithium disilicate glass ceramic	IPS e.max Press Ivoclar Vivadent	1.5 or 3.0 mm thick discs Shade A2 1.0, 2.0 or 3.0 mm thick discs Shade MO1 1.0 mm thick discs Shade A1 0.5 or 0.8 mm thick samples with veneer layer on top Shade LT, MO or HT	20 or 40 s at 600 mW/cm ² 10, 20, 30, 40, 50 or 60 s at 584 mW/cm ² 20 s at 1200 mW/cm ² 40 s at 1000 mW/cm ²	3 mm samples significantly reduced DC (52.9%) of Calibra at room temperature ⁵⁰ Light intensity decreased ~ 62% under 1 mm, 86% under ~2 mm and 92% under ~3 mm thick samples. Light exposure of 30 s or longer may compensate for the 1 or 2 mm thick discs blocking the light ⁷⁹ Final restoration color less influenced by cement shade, contrast ratio less affected when light-cured with 470 nm wavelength, no influence on mechanical properties of the resin cement underneath ⁵¹ The higher the opacity of the ceramic, the lower the DC of dual-cured cements; similar DC between 1.5 and 2.0 mm thick samples ¹³
	IPS e.maxCAD Ivoclar Vivadent	0.5, 1.0, 2.0 or 3.0 mm discs Shade MO1 or MO4	5, 10 or 15 s at 1600 mW/cm ²	Reduced hardness with 1 mm or thicker samples, irrespective of the length of light exposure ³⁵
Leucite reinforced glass ceramic	IPS Empress Ivoclar Vivadent	1.0 mm thick discs Shade not informed	10 s at 580~1650 mW/cm ²	Light transmission reduced by ~55% through 1.0 mm thick samples ⁵⁸
	IPS Empress CAD Ivoclar Vivadent	1.0 mm thick discs Shade A1	20 s at 1200 mW/cm ²	Final restoration color more influenced by cement shade, contrast ratio more affected when light-cured with 470 nm wavelength, no influence on mechanical properties of resin cement underneath ⁵¹
	IPS Empress 2 Ivoclar Vivadent	1.0, 1.5 or 2.0 mm thick discs Shade A2	60 s at 800 mW/cm ²	No effect of ceramic thickness on bond strength between substrate and resin cement ³
	IPS Empress Esthetic Ivoclar Vivadent GN-I GC Corp. ProCAD Ivoclar Vivadent	0.7, 1.4 or 2 mm thick discs Shade A3 1.0, 2.0 or 3.0 mm thick discs Shade A3 0.5, 1.0, 2.0 or 3.0 mm discs Shade E100 or bleach	40 s at 605 mW/cm ² 3 cycles of 800 mW/cm ² 5, 10 or 15 s at 1600 mW/cm ²	Light intensity decreased ~20% under 0.7 mm, 36% under ~1.4 mm and 57% under ~2 mm thick samples. No significant differences observed in DC of resin cements ⁴⁷ Negative correlation between cement hardness and ceramic thickness, with significant decrease starting from 1.0 mm thick samples ⁴⁶ 15 seconds light exposure compensates for reduction in light transmittance in up to 2 mm thick samples ³⁵
Glass-infiltrated alumina composite	In-Ceram alumina Vita Zahnfabrick	0.5 or 0.8 mm thick sample with veneer layer on top Shade A2	40 s at 1000 mW/cm ²	Significantly decreased DC for both dual- (37~54%) and light-cured (24~30%) cements and both thicknesses ¹³
Polycrystalline zirconia	ZR Ceramill Zi	0.5 or 0.8 mm thick sample with veneer layer on top Shade A2	40 s at 1000 mW/cm ²	Significantly decreased DC for both dual- (17~25%) and light-cured (22~24%) cements and both thicknesses ¹³
Polycrystalline alumina	Procera Nobel Biocare	0.25 or 0.6 mm core thick discs with veneering material on top to equal 1.0 mm	10 s at 580~1650 mW/cm ²	Both core thicknesses blocked conventional halogen light completely; 0.25 mm core reduces Plasma Arc light by 66% and 0.6 mm by 79% ⁵⁸
Feldspathic porcelain	Ceramco II Dentsply Ceramco	1.0 mm thick discs Shade not informed	10 s at 580~1650 mW/cm ²	Light transmission is reduced by ~63% through 1.0 mm thick samples ⁵⁸
	IPS InLine Ivoclar Vivadent Vita VM7 Vita Zahnfabrick	1.5 or 2.0 mm thick discs Shade A2 2.0 mm thick discs Shade OM1, 2M2 or 5M3	40 s at 1000 mW/cm ² 20 or 40 at 900 mW/cm ²	No significant reduction in DC, irrespective of sample thickness ¹³ The darkest shade significantly reduced DC of resin cements at both light activation times; when darker ceramic and darker resin cement are associated, 40 s light activation may significantly increase DC ⁵²
Micro-hybrid indirect resin composite	Sinfony 3M ESPE	1.5 mm thick discs Shade D A3	40 s at 800 mW/cm ²	DC of resin cements reduced from 1.5 up to 33% depending on the luting system used ⁷²
	Signum Heraus	2.0, 3.0 or 4.0 mm thick discs Shade A2	40 s at 1200 mW/cm ² 60 s at 800 mW/cm ² 120 s at 400 mW/cm ²	DC decreased ~21% for samples cured under 4 mm discs when compared to samples cured under 2 mm; no significant influence of the curing protocol on the DC ¹

&Brand names mentioned were reproduced from the research papers included in this literature review. Therefore, there may be other brand names currently in the market that would represent the categories of materials described in this Figure. DC=degree of conversion

Figure 2- Correlation between indirect restorative materials and the curing properties of the resin cement underneath

group, activated under direct light exposure¹⁴.

When the impact of the shade of the ceramic system is evaluated, it can be observed that if shades with higher chroma are used, less energy reaches the cement layer, since dark pigments absorb a significant amount of light⁹, negatively influencing the cure of light-dependant cements. Dual-cured cements light-activated under 2 mm-thick samples of darker dentin shade of feldspathic porcelain present significantly lower DC than cements light-activated under lighter shades⁵³. When yellow and translucent shades of a resin cement were light-activated under the darker porcelain, only prolonged light-exposure time (40 seconds) was capable of increasing the DC of the cement yellow shade⁵³, indicating that the combination of darker shades in both the cement and the indirect restorative material compromise the overall DC of the cement layer.

With regard to laminate veneers, some studies show that although the bond strength between veneers and tooth structure is not affected by shade or opacity of the ceramic system, the DC of the cement may be diminished by either thicker, darker or more opaque restorations¹⁵, frequently used to mask severely darkened teeth, and a lower DC of the cement layer may compromise the esthetic result due to the continuous discoloration of the material⁷⁵. The analysis of the DC of a light-cured resin cement after the superimposition of different veneer materials with different thicknesses indicated that the effect of light attenuation on the degree of conversion is not significant only for ceramic thicknesses of 1.0 mm or less⁶².

Considering the optical properties of the indirect restorative composites, there are different factors playing a role in light transmittance, such as particle size distribution, thickness of the restoration and shade. The smaller the particles, the more interfaces will be present acting as light scattering centers³³, consequently increasing the opacity of the material employed, which indicates that larger particles allow for deeper activation of the cement layer by light^{4,57,58}. Interestingly, the hardness of dual resin-based cements is less affected when photo-activation is performed through an indirect restorative composite – either microfilled or micro-hybrid – than when it is performed through an all-ceramic system – lithium disilicate and glass ceramic⁵⁷. When the effect of thickness is evaluated, there is indeed an inverse correlation between thickness of an indirect composite resin restoration and Knoop hardness of the resin based luting system²⁶. Dual resin cements cured under 2 mm-thick micro-hybrid composite samples show significantly lower DC than samples cured under ideal conditions³⁰, and the DC of dual cements is 12% lower under 4 mm onlays in comparison to that

measured under 2 mm thick onlays¹. With regard to the effect of shade on indirect composite resin light transmittance, Arrais, et al.⁸ (2008) demonstrated that only 11% of light reaches the cement layer when cured through a 2 mm microhybrid composite A2 shade as opposed to 8% when A4 shade was employed, but no effect on DC was observed for dual-cured resin cements with higher concentration of benzoyl peroxide. The authors pointed out that the adhesive component also presented a chemical activator of the polymerization and could, therefore, compensate for the absence of light⁸.

LIGHT CURING DEVICE

It has been demonstrated that the hardness of dual-cured cements is dependent on the level of exposure to the curing light³². As previously mentioned, the component responsible for the chemical activation of the material cannot compensate for the total absence of light^{3,32}. The higher the light intensity and the longer the exposure time of the resin cement, the higher the Knoop hardness of the dual-cured materials⁶⁴. However, even when under direct light exposure, there is a limit above which the DC of a photo or dual-cure cement cannot be increased⁴⁴.

Quartz-tungsten-halogen (QTH) light curing units (LCU) deliver light irradiance varying between 400 and 1360 mW/cm²^{17,50,64}. When exposure time (40 s, 60 s or 120 s) and intensity (1200, 800 or 400 mW/cm²) of light exposure on DC of dual cements was evaluated, different materials showed different results¹, although all the associations resulted in the same amount of energy (48 J). Activation of dual cements under 2 mm resin composite onlays using low light intensity for prolonged time presented a trend towards higher DC, probably due to the slow increase in the material viscosity, allowing more monomers mobility¹.

Light-emitting diodes (LED)-based units were introduced in the market in 2001⁷⁶ and are another option to activate photo-cured resin cements. These units generate light under a narrower spectrum (between 450 and 490 nm) with the peak around 468 nm, the ideal wavelength for resin-based materials using camphorquinone as the photoinitiator¹⁷. When the photo-activation of a cement is performed through a ceramic system, light transmittance increases for higher wavelengths⁵⁷. The higher mean wavelength of LED lights improves the capacity of the equipment to activate resin cements under indirect restorations^{36,76}. However, light-intensity is also critical, since LED with relatively low light intensity (320 mW/cm²) results in decreased Knoop hardness at the bottom of dual-cured cement samples⁵³.

The effect of QTH (905 mW/cm²) and LED (1585

mW/cm²) curing units on Knoop hardness of resin-based cements indicated that there was no effect of LCU on the hardness of dual-cure cements⁵⁴. Samples cured under 1.4 and 2.0 mm ceramic slabs (leucite glass ceramic, shade A3) showed lower hardness values than samples cured under direct light exposure and under 0.7 mm slabs⁵⁴. Authors observed that hardness on dual-cured luting agents may not be dependent on the light source, as long as the irradiance level for the effective wavelength region to activate the photo-initiator is similar⁵⁴.

With the application of high-power curing units in dentistry, LED-based equipment with high light intensity (1000-1600 mW/cm²) are being advertised as an alternative to reduce the curing time of resin-based materials. However, the minimum time required to properly cure a dual-cured luting system is 15 s under ideal conditions, so that maximized mechanical properties can be obtained³⁶. Therefore, it is not recommended to reduce the light exposure time to less than 15 seconds on each side of a restoration, irrespective of light intensity³⁶. Indeed, it has been demonstrated that light-curing a dual-cure cement for 9 s with a LED device (1100 mW/cm²) results in significantly reduced degree of conversion⁴¹. The authors observed that exposing dual-cure material to high intensity light may increase its viscosity more rapidly, hindering the migration of active radical components responsible for further polymerization⁴¹. Similar results were obtained when LED device (1100 mW/cm²) with different activation modes and QTH (600 mW/cm²) were used to photoactivate resin cements between ceramic samples (lithium disilicate) and human dentin, and the authors found out that groups photo-activated for 10 s presented inferior bond strength⁵⁰. Higher bond strength results were obtained when LED devices under exponential mode and QTH were used, and since the exponential mode was applied for twice as much time as the other LED groups, the overall energy delivered was increased, which may have enhanced the DC⁵⁰. Authors also observed that higher light intensity produces higher contraction strains during resin polymerization, which may promote debonding at the adhesive interface⁵⁰. Therefore, prolonged exposure times are desirable not only to increase the energy delivered to the luting material, in an attempt to compensate for the attenuation of the light promoted by the indirect restorative material, but also to reduce stress generation at the cement-substrate interface, to ensure preservation of the bonding.

A comparison of different light curing equipment (QTH – 600 mW/cm²; LED – 1400 mW/cm²; argon ion laser – 600 mW/cm²) used to activate resin cements under 2 mm-thick samples of composite resin indicated that the degree of conversion

of the resin cements is again more related to the commercial brand and, consequently, to the material composition than to the curing device itself, with LED and argon ion laser devices resulting in lower DC for one of the materials in the photo-cured mode⁶⁹. Although the short range of the spectra peak for LED devices may be advantageous when curing under ceramic systems, a wider range may be clinically interesting to photo-activate alternative photoinitiators, promoting a higher DC for QTH lights even in the presence of lower light intensity.

In addition to the factors presented above, there are other variables playing a role in the DC of light-activated resin-based cements, such as the distance between the tip of the curing device and the cement layer^{4,52,75} and other indirect factors reducing the light intensity being delivered^{38,50,52,59}. Based on the results presented and the number of studies indicating that prolonged light-activation may be beneficial for the DC of dual- or photo-cured cements^{43,53,80}, increasing the light exposure time, even though this would mean a couple more minutes of clinical procedure, would be certainly beneficial for the clinical performance of an indirect restoration.

CONCLUSION

The clinical success of an indirect restoration is not only attributed to the DC of the resin cement or to its mechanical properties, since there are other aspects that determine the clinical performance of dental prostheses. Nonetheless, ensuring a high DC is paramount to obtain the best out of the chemical and physical properties of the resin cement, besides being a critical factor for biocompatibility. When performing a luting procedure, one should pay attention to the characteristics of the indirect restorative material to be employed, and make a conscious decision of using a cement system that would be more indicated to the clinical case necessities. Curing modes and the best light-curing technique are examples of information that is to be available. It is crucial for clinicians to know and understand the cement systems they are working with.

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